DUNE VEGETATION MONITORING - 2005

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Table of contents

Executive summary

In 2005, a dune vegetation monitoring project was conducted to provide a foundation for the development of a long-term monitoring protocol. Sampling sites were established throughout the Seashore, arranged in transects running perpendicular to the coastline from Chatham to Provincetown. Vegetation communities were surveyed, along with a number of abiotic variables including salt spray, wind strength, changes in ground surface topography, and soil properties. Sites were further characterized using GIS technology to derive mean aspect, slope, and distance to the ocean. A broad classification of landscape age was done using existing information about the geophysical evolution of Cape Cod and aerial photography.

Dune plant communities within the monitoring network were diverse and reflected the influence of environment and geologic history. A total of 44 vascular plant species were recorded, 7 of which were introduced exotics. One state listed species, *Corema conradii* (Species of Special Concern), was found at a single site. Species richness was highly variable, ranging between 2 and 17, with a mean value of 7. In terms of abiotic factors, salt spray and sand burial were influential, but only at sites in close proximity to the coastal bluffs along the east-northeast part of the shoreline. On average, communities on the glacial outwash plain were more species rich with more woody forms – a characteristic that is most likely the consequence of a longer period of succession. Higher amounts of organic matter and lower soil pH were observed at older sites. In contrast, younger sites on accreting landforms had fewer species, fewer woody plants, less organic matter in the soil, and higher pH values. These findings, along with observations from previous studies, are embodied in a conceptual model that describes the basic structure and functioning of this system.

Introduction

<u>Background</u>

Coastal dunes make up roughly one third of the Cape Cod National Seashore (CACO), covering approximately 8,500 acres from Chatham to Provincetown. Dunes predominate on barrier beach and spits, along the coastal margins of the Atlantic Ocean and Cape Cod Bay, and across the northern tip of the peninsula – an area known as the Province Lands (Figure 1).

The Province Lands began forming soon after glacial retreat (~18,000 y.b.p.) as eroded sediments from the outwash plain were transported north and deposited by longshore currents. Sand from the beaches of this elongating hook was then blown inland to form the dunes. Although mature forest eventually became established here, most of the vegetation was removed by Europeans settlers for use in building and to clear land for agriculture and livestock grazing. This resulted in a rapid destabilization of the ground surface and by the mid 1800s the area had been converted to a sparsely vegetated system of shifting dunes.

Smaller areas of dunes are located along the edges of the glacial outwash plain. This part of the landscape is much older and present-day dunes are created and sustained through wind erosion of the bluffs with subsequent inland sand deposition. On newer landforms, such as barrier beaches and spits, sand accretion and overwash events continue to create dune habitat. Collectively, these processes have resulted in major changes in the geomorphology of Cape Cod over time.

Figure 1. Map depicting 2000 aerial cover of dune grassland habitat (green) within CACO and examples of dune landscapes from selected areas.

Vegetation

CACO dunes are variably covered with vegetation, some of which has established naturally and a small portion of which was planted at various times in an attempt to minimize dune migration (Madore and Leatherman 1981). Dune communities can be broadly distinguished from heathland communities by an abundance of *Ammophila breviligulata* (American beachgrass), one of the reasons they are often referred to as "dune grasslands". Ericaceous shrubs and sub-shrubs predominate in heathlands and are generally considered to be an advanced successional stage (Gwilliam 2004).

Successful dune species have xerophytic characteristics and can tolerate hot, dry, and sometimes salty conditions. Plants have various adaptations such as a thick, waxy cuticle to limit water loss. In the case of *A. breviligulata*, the leaves roll up during hot, dry weather, which reduces transpiration. Common plant species of the dunes include *A. breviligulata*, *Solidago sempervirons* (seaside goldenrod), *Toxicodendron radicans* (poison ivy), *Artemesia campestris* ssp. *caudata* (wormwood), *Morella pensylvanica* (northern bayberry), and *Prunus maritima* (beach plum). In interdunal depressions that are low enough to intersect with the groundwater table for part of the growing season, seasonal wetlands form and support distinct hydrophytic communities. These wetlands, also known as dune slacks, were the subject of a separate study in 2003-2004 and are described in Smith and Hanley (2005).

A number of environmental factors have been shown to influence dune plant communities and their patterns of succession or regression. Wind can cause direct physical damage (known as "wind pruning") to the structural integrity of plants (particularly woody species). Wind also carries salt spray, which can affect plant foliage and/or roots (Wilson and Sykes 1999, Griffiths and Orians 2003a,b, Griffiths and Orians 2004) although it has been suggested that the latter may only affect a handful of susceptible species growing in close proximity to the ocean (van derValk 1974). Sand transport (sandblasting, burial, erosion), drainage, soil organic matter, and general climatic variables such as temperature, precipitation, etc. (Vestergaard 1991, Hesp 2004, Ripley and Pammenter 2004) also regulate plant community dynamics. However, the relative influence of these factors may vary considerably by geography. For example, in dune systems of arid environments, soil moisture is more critical to growth and survival than temperature regions (Hesp 2004).

Rationale for monitoring dune vegetation

In addition to their aesthetic appeal to visitors, the dunes provide habitat for a variety of flora and fauna that are largely confined to this environment. Plants such as *Polygonella articulata* (sand jointweed) and *Cyperus grayi* (dune flatsedge) occur almost nowhere else within CACO. Vast expanses of lichens, bryophytes (mosses and liverworts), and mushrooms occur as well. The dunes are home to many species of wildlife such as the hognose snake and Fowler's toad. Moreover, the Province Lands are a population center for the endangered Eastern Spadefoot toad. From a landscape perspective, the dunes constitute early successional, open habitat that is rapidly disappearing on Cape Cod through the process of succession.

Numerous natural and anthropogenic factors may influence this ecosystem, including chronic and episodic climatological factors, invasive species, precipitation quality and quantity, air quality, and global warming. Plant communities responding to these influences will, in turn, control dune migration, which can be alternatively suppressed and re-activated depending on vegetation changes on the land surface. Thus, understanding spatial and temporal patterns in dune vegetation communities is important from a management standpoint and in predicting landscape-level change.

While numerous studies on CACO dune vegetation have been conducted in the past, they have been rather limited in scope and largely focused on the Province Lands. In addition, the survey methods were not designed with long-term monitoring in mind. Most importantly, the vast majority of studies were done before the advent of GPS technology. As such, it would be extremely difficult, if not impossible, to resample any of the original sites. To reliably monitor how the system evolves through time and responds to these influences, a standard, repeatable protocol is necessary. This report summarizes the methodology and results of a draft long-term monitoring plan for this system.

Methods

Site selection

CACO's vegetation map, created from 2000 aerial photography, was used to generate ten random sampling locations from within upland dune community polygons (Arcview 3.2 randomization extension). From this group of starting points, seven were selected for monitoring since it soon became apparent that it would be nearly impossible to collect data from that many sites in a single day - a necessary requirement for some of the environmental variables which can fluctuate substantially from day to day. Sites were established at distances 0, 50, 100, 200, 300 m (etc) away from the coastal bluff in a direction perpendicular to the shoreline (see Appendix I). [Note: in the text and figures of this report the sites are labeled DG(transect number)-1 (bluff site), DGx-2 (50-m site, DGx-3 (100-m site), etc. Transects include DG1, DG3, DG4, DG5, DG6, DG7, and DG9. There is no DG2 or DG8 (originally placed but not monitored).]

At each site, zinc-plated steel dowels were hammered into the sand. Two more dowels were later established to delineate the corner points of two 10 x 10 m plots, opposite one another and centered on the original site marker (Figure 2). The dowels were pounded in to a depth of 70 cm below the ground surface, leaving 30 cm above so that sand accumulation or erosion could be measured over time. This is analogous to the use of erosion pins, a method commonly used to track ground surface changes in dune systems (Jungerius et al. 1991).

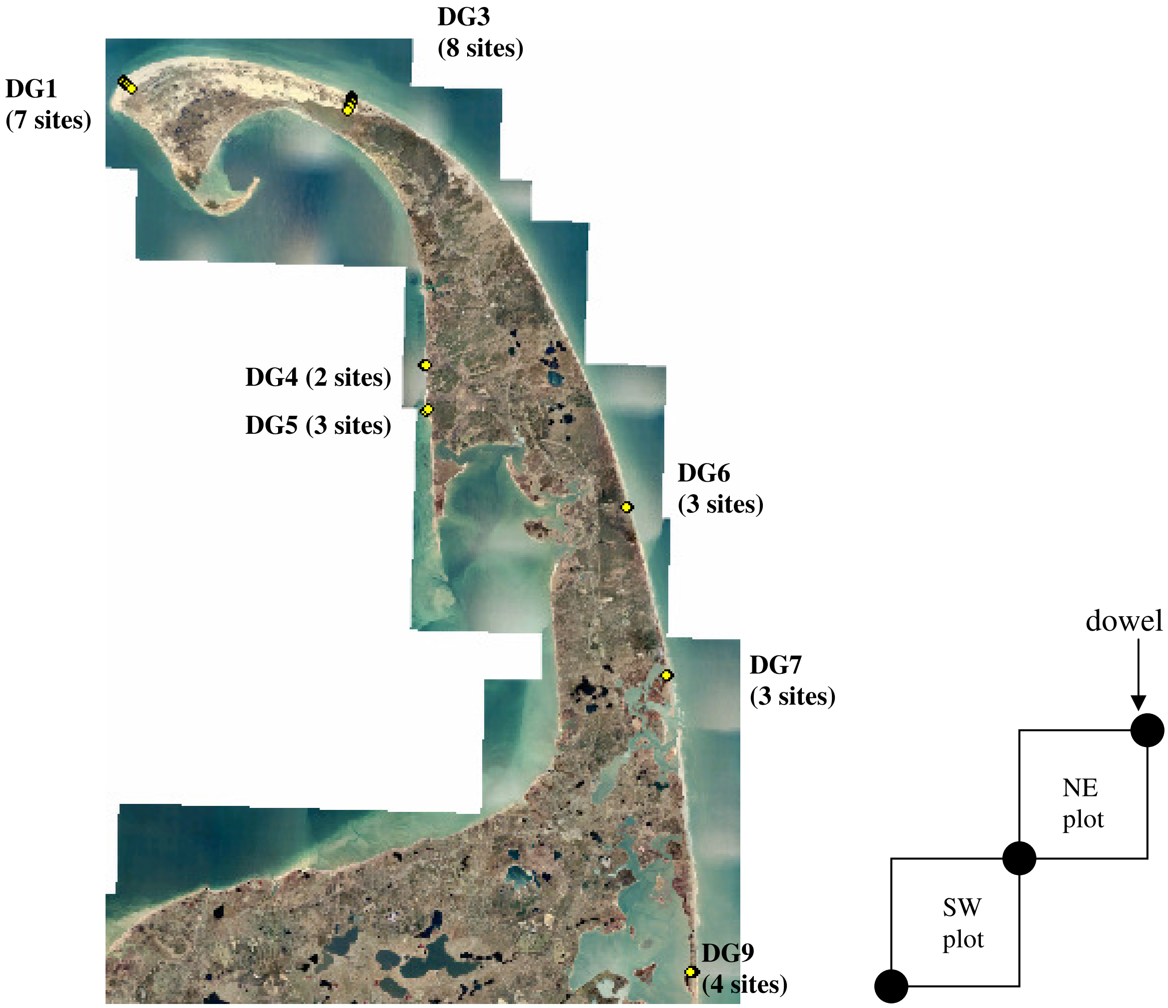

Figure 2. Map of dune grassland (DG) transect locations and site layout (see Appendix I for close up images of site locations within each transect).

Vegetation survey

The cover of all species occurring with each plot was assessed visually according to the Braun-Blanquet (1947) scale (0=0%, 1=>0-1%, 2=1-5%, 3=5-25%, 4=25-50%, 5=50-75%, 6=75-100%). Total cover per site (i.e., the area encompassed by the NE and SW plots) was then calculated as the summed cover values for each species. Determination of whole site cover was done in this manner (i.e., sum of two plots) because a 100 m^2 plot nears the area limit of what can reasonably be assessed using visual estimates of cover. The cover of soil algae, lichens, mosses, and bare ground was also recorded. In addition, the heights of the nearest *Ammophila breviligulata* plants (beachgrass) at locations 3m, 6m, and 9 m along a diagonal line between the two corner markers were measured as an indicator of beachgrass vigor. Finally, oblique angle digital images of each plot, taken from the site center pole looking toward the corner pole, were acquired.

Environmental conditions

Airborne salts were trapped by two polyester paint rollers (3 x 7 cm Ace Hardware™ mini rollers) attached to an aluminum bar (spaced ~6cm apart), which itself was fastened to a steel dowel at a position 30 cm from the ground surface (Figure 3). Vegetation was cleared from a 50 cm radius from the dowel so that vegetation would not interfere with deposition. Underneath the rollers, two clear plastic cylinders (open at the top, closed at the bottom) were placed to catch any water dripping from the rollers during and after rain events. Salt could enter the cylinders either directly by passage through the open top) or indirectly (washed off the rollers by precipitation). This method of capture essentially follows the design of Wilson and Sykes (1999). At 3 different times during the growing season (May - October), the rollers were rinsed with deionized water using a squirt bottle, with the rinse water falling into the cylinders below. The total volume of water in each cylinder was then measured and a conductivity reading taken. Cylinders were also placed in a sheltered area back at the laboratory to serve as a "controls". Conductivity values were standardized by volume (calc) and expressed as units of conductivity per collection tube (minus reference site values, which represent rainwater input).

Tatter flags were used to assess the relative "windiness" of sites as per Edwards and Claxton (1964) and Wilson and Sykes (1999). Two flags (each 61 cm^2) made of 100% cotton were fastened to the top of the steel dowel marking the middle of each site (Figure 3). Over time, the deterioration of the flags (loss of area) was estimated by measuring the area of intact material. Fortunately, the flags tended to deteriorate in a manner which left square blocks of material intact, so measurements of length/width of each of these blocks could be measured using a small ruler and summed to quantify total area remaining (Figure 3).

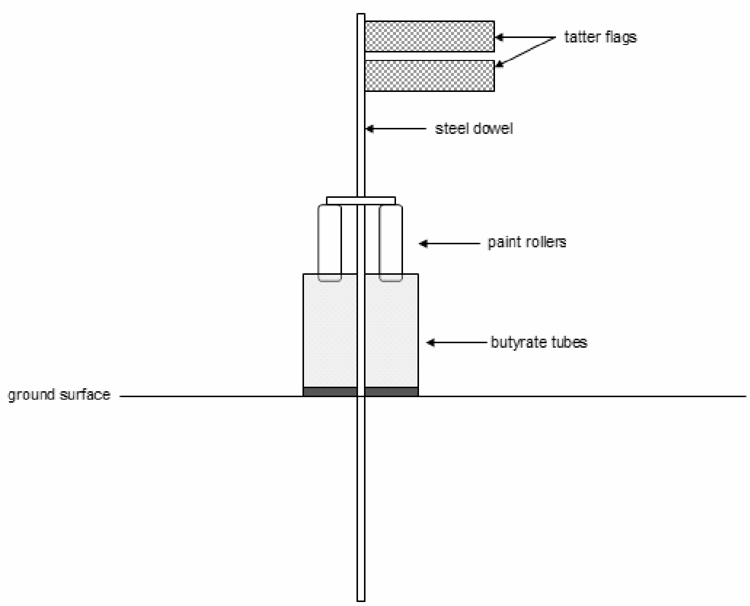

Figure 3. Diagram of salt spray and wind monitoring apparatus.

The net amount of burial or erosion during the period from May to December was quantified by measuring the distance from the top of the steel dowels marking the plot corners to the ground surface. For soils analysis, approximately 50 cc of topsoil was collected from each subplot by coring with a (plastic tube (10 cm length x 3 cm diameter) in January 2006. The samples were immediately dried at 80°C to a constant weight and then sent to Brookside Laboratories, Inc. (New Knoxville, Ohio) for analysis of soil pH, % organic matter, and concentrations of sulfur, phosphorus, calcium, magnesium, potassium, sodium, iron, and aluminum.

GIS-derived variables

Distance to the ocean was determined using ARCGIS 9.1 measurement tools. Distance was characterized in three ways: 1) the shortest path (straight distance), 2) distance along a NE bearing (45°), and 3) distance along a NW bearing (315°). These bearings were chosen because the strongest winds blow from these directions during the early and late parts of the growing season (Madore and Leatherman 1981). Southwesterly winds, which prevail during the summer months, are generally much lighter.

Because exposure to wind is influenced by surrounding topography, a metric was developed to account for "sheltering" features of the landscape. From the center point of each site, 100-m lines oriented along NE and NW axes were drawn in ArcMap 9.1 and then interpolated based on a digital elevation model (DEM). The data at every 10 interval along these interpolated profiles were then extracted. The distance to the nearest point at which the elevation was higher than the origin of the line (i.e., the site) was divided by the difference in elevation between the two. As such, a measure of relative exposure to NE and NW winds was generated. High values indicate protection from the wind by a close, elevational high point in front of the site. Low values indicate almost no shelter or full exposure. GIS was also used to derive various topographic data for each site. Mean elevation, aspect, and slope were determined from the DEM within a 300 m^2 circular area (14 m radius), which encompassed the two subplots at each site.

Age of the landscape could only be categorized in a very general way. Age groups were based on Uchupi et al. (1996) (Figure 4) and on existing aerial photography that shows erosion and accretion along the coastline from 1938 to 2003. The sites along transects DG1, DG7, and DG9 were classified as "young" since they exist on post-glacial landforms that developed relatively recently. In contrast, sites along transects DG4, DG5, and DG6, which are part of the glacial outwash plain, were classified as "old". Although transect DG3 is on the postglacial part of the peninsula, it was also classified as old, the justification being that its proximity to the High Head region of CACO indicates that it was one of the first features to form after glacial retreat.

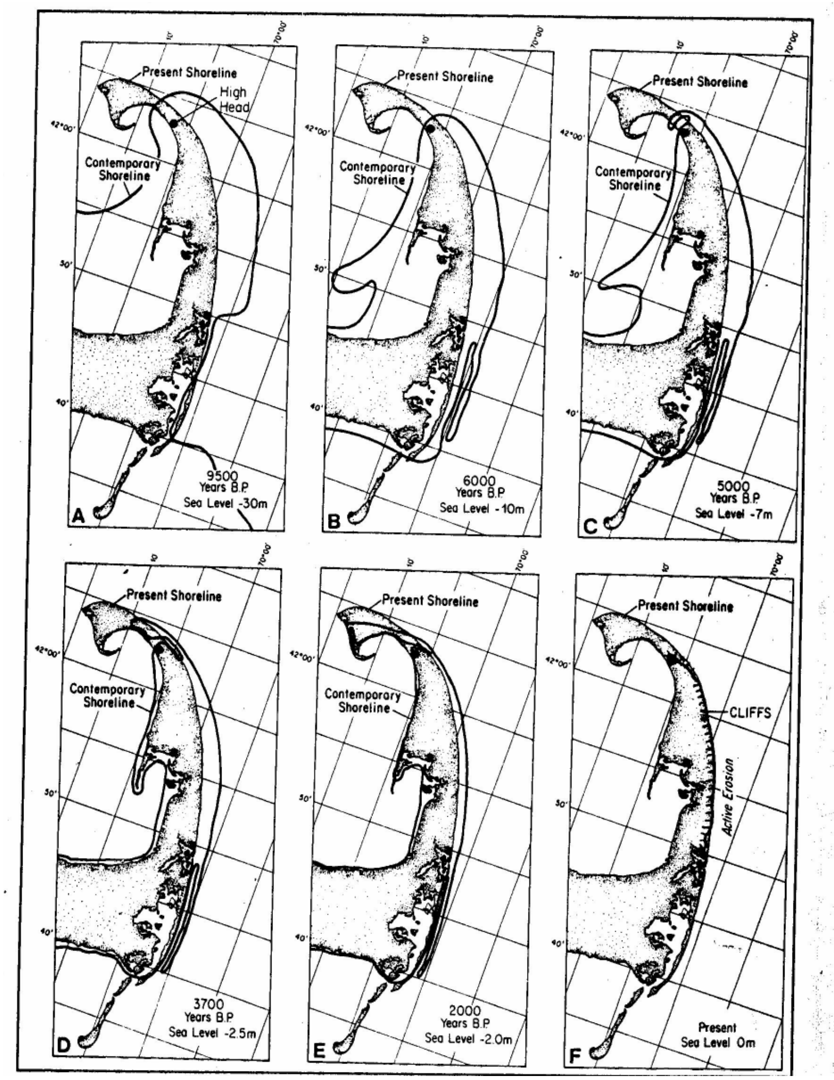

Figure 4. Late quaternary formation of lower Cape Cod (from Uchupi et al. 1996).

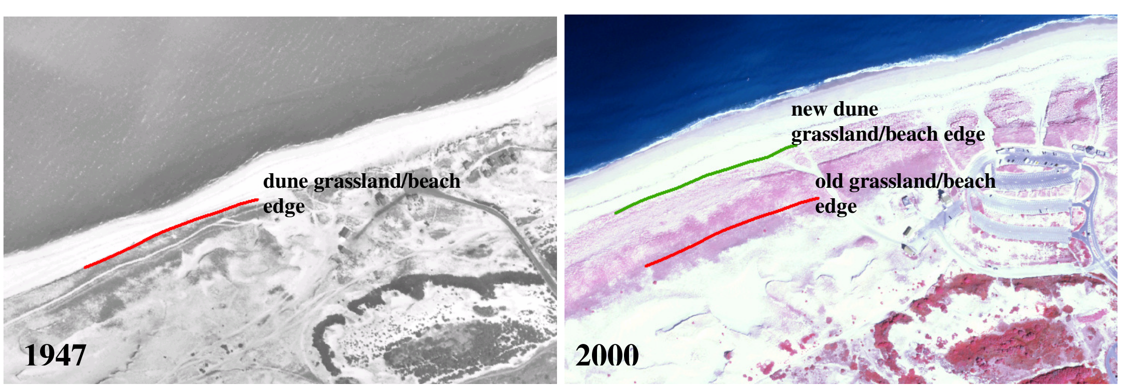

Figure 5. Coastal accretion as shown by the seaward extent of dune grassland vegetation in 1947 (left, red line) vs. 2000 (right, green line).

The final component of monitoring for each site included the acquisition of digital images in August 2005. Each subplot was photographed from the center dowel facing toward the opposite corner of the plot. The images were downloaded and stored on the NACL server at Y:\Images\Dune_grassland\DG_plots_photos_Aug05.

<u>Data analysis</u>

All environmental variables were log-transformed to satisfy the assumptions of normality and homoscedasticity. Principle Components Analysis (PCA) and multidimensional scaling (MDS) were used to explore variability in community composition and environmental properties. Primer's BIOENV routine, which is analogous to Canonical Correspondence Analysis, was helpful in evaluating the relative importance of environmental variables in explaining taxonomic variation. In this procedure, a similarity matrix based on normalized Euclidean distance is generated from log-transformed environmental data. This is then compared to a Bray-Curtis similarity matrix of square root-transformed species cover values. Using XL-Stat (ver. 7.5.2), both single and multiple regression was used to explore relationships between of biological and environmental variables.

Results

<u>Environmental conditions</u>

Salt spray showed a relatively consistent spatial pattern among transects, with DG3, DG6, and DG7 exhibiting the highest amounts of deposition throughout the sampling period (Figure 6). Samplings on May 13 and June 3 occurred shortly after major northeastern storm events and showed the highest levels. In comparison, there was little deposition during the June-July period.

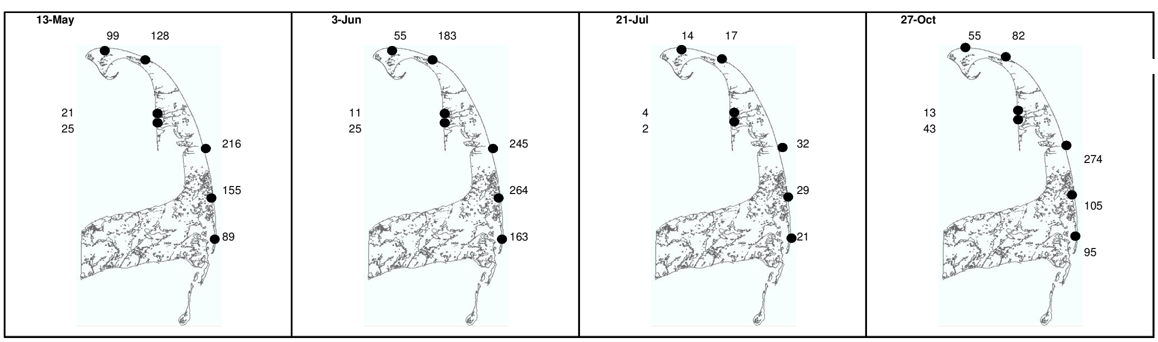

Figure 6. Mean salt spray deposition (collector tube conductivities) by transect and date (values in mS; black circles represent transect locations).

When broken down by site, spatial variability in mean deposition among sites is apparent (Figure 7). Along transects DG1, DG 3, DG 6, and DG 7, sites closest to the coastal bluff had the highest amount of salt deposition. Levels quickly declined and were quite variable with increasing distances away from the bluff. Transects DG4 and DG5 had uniformly low deposition values with no clear spatial pattern. Sites DG1-6 and DG9-4, which are located at the edge of salt marshes, had enormously high conductivity values and it is likely that these tubes were inundated by Spring tides.

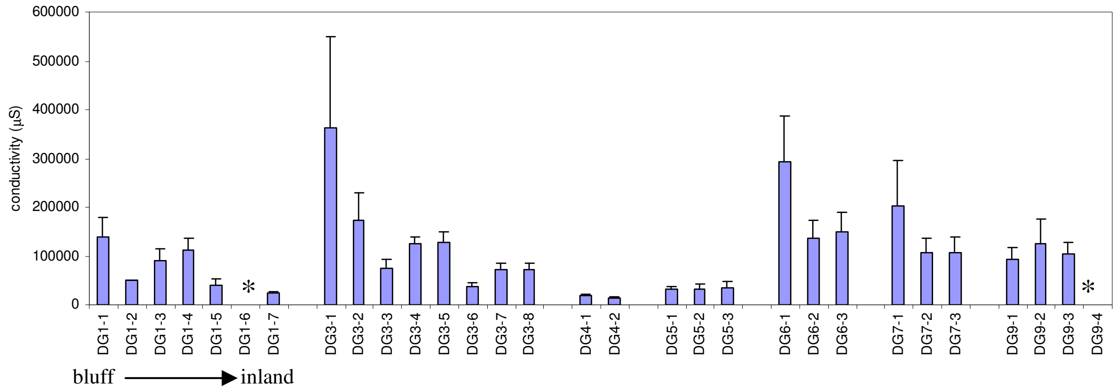

Figure 7. Salt spray deposition by site (asterisks indicate where data was excluded due to suspected inputs of seawater from Spring tides; error bars are standard error of the mean).

Multiple regression revealed that mean elevation and distance to the ocean along a NE bearing were important in determining salt spray deposition. The equation of the model showed that conductivity was negatively correlated with distance to the ocean along a NE bearing and positively correlated with elevation (R^2= 0.74). For any single variable, mean salt deposition showed the best correlation with distance to the ocean along a NE bearing as described by a power function (Figure 8). The similar R^2 value for this single variable regression analysis suggests that it is primarily distance that determines salt spray deposition and that elevation plays a comparatively minor role.

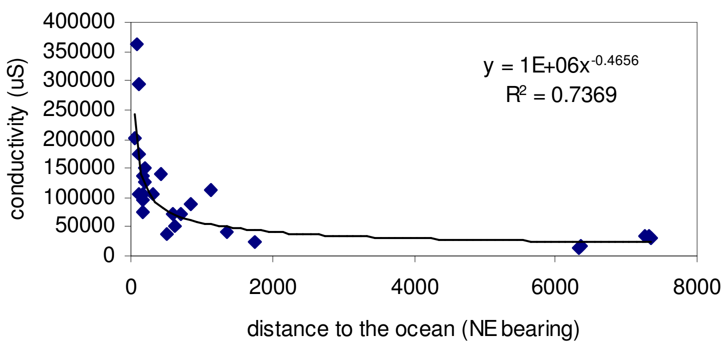

Figure 8. Power curve of salt spray deposition vs. distance to the ocean along a NE bearing.

Patterns of tatter flag deterioration essentially mirrored that of salt deposition in that transects DG3 and DG6 showed the most deterioration (Figure 9). Unfortunately, the two replicate flags at DG1-2 and one flag at DG1-5 and DG1-7 were had been lost by October. Presumably they were ripped from the dowels by strong winds. Thus, the transect means for this date do not include these sites. The largest flag area losses occurred during the May - June period (during which time there were two Nor'Easters), with relatively slow rates of loss thereafter.

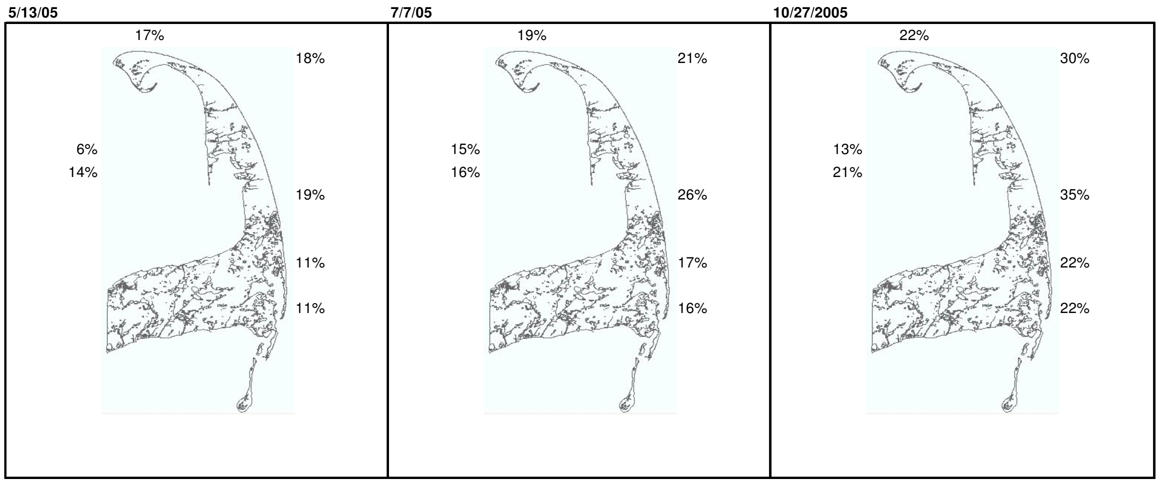

Figure 9. Cumulative flag area loss from May – October (mean %) by transect and date.

Data from individual sites show that some transect mean values were strongly biased by large amounts of tatter at sites closest to the coastal bluff, particularly sites DG3-1 and DG6-1. Figure 10 shows flag area loss from May – July (October was not included due to loss of flags at 3 sites mentioned above). For sites further inland along the transects, flag area loss was generally lower with no clear spatial pattern.

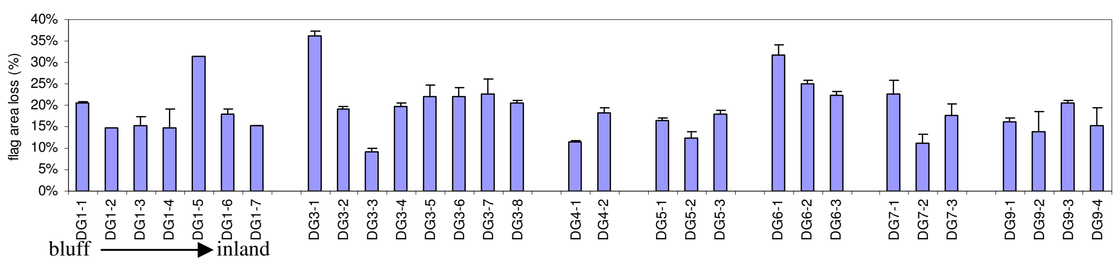

Figure 10. Mean total flag area loss by site from May – July (error bars are standard error of the mean).

Linear regression showed that tatter was fairly well correlated with salt spray (Figure 11) but could not be adequately described by any other single variable, including the indices developed for wind exposure based on surrounding topography.

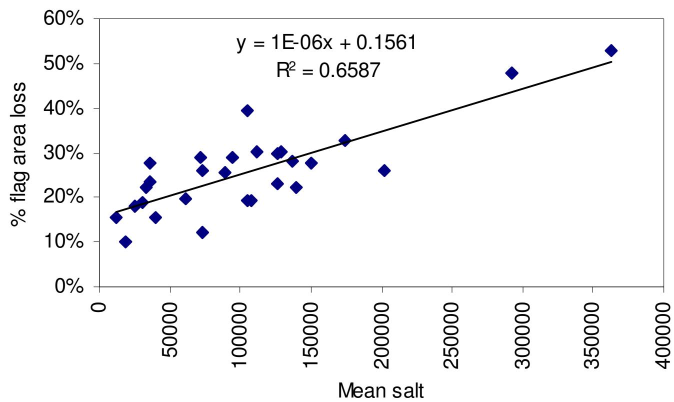

Figure 11. Mean flag area loss (%) vs. mean salt deposition.

Analysis of mean flag area loss by multiple regression showed that distance to the ocean along a NE bearing and mean elevation were the best combination of variables to explain tatter values. Like salt spray, the regression model suggests that flag area loss is negatively related to distance and positively related to elevation. However, the correlation is relatively weak with an R^2 of only 0.32. Interestingly, when only bluff sites are considered, losses are more strongly related to elevation (Figure 12).

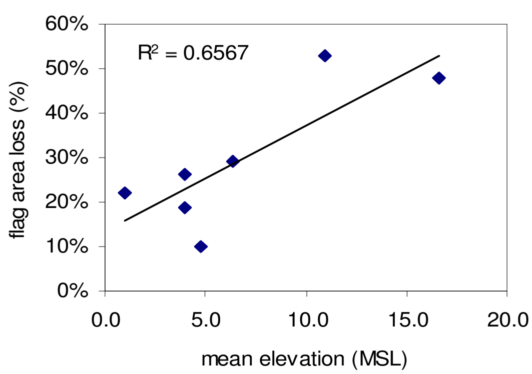

Figure 12. Flag area loss vs. mean elevation for bluff sites only.

Large changes in ground surface elevations, as determined by erosion pin measurements, were, with the exception of DG3-8 which is a NE-facing dune blowout area, limited to bluff sites (Figure 13). Accumulations of up to 8.5 cm of sand (DG7-1) were measured. Within each of these sites, burial was much greater at the pole closest to the bluff edge (the NE corner), which accounts for the large error bars in Figure 13. At DG6-1, substantial erosion occurred. In fact, it will not be long before this plot disappears as the bluff edge erodes westward. Plots along the edge of Cape Cod Bay did not show any sand accumulation, which indicates that NE storms are the principal cause of major sand movement during 2005. Similarly, the majority of inland sites showed little change.

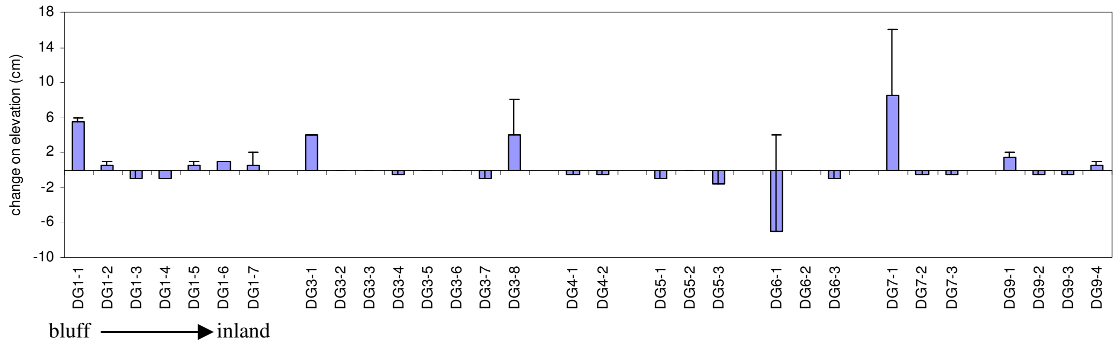

Figure 13. Accumulation or erosion of sand by site as determined by erosion pin measurements (values are means of the two corner dowels; time period represents May - December 2005; error bars are standard error of the mean).

Soil pH ranged between 4.55 (DG3-3) and 6.8 (DG1-1), the latter of which is the youngest site within the monitoriung network (Table 1). Along individual transects, pH was generally highest at the bluff edge sites and lower and variable at inland sites. Soil organic matter exhibited much larger variability, with high values occurring at DG3-3, DG5-2, and DG5-3. Spatial trends along the transects were not evident. Among cations, only Na showed trends, generally highest at bluff edge sites. Ca, Mg, and K, were highly variable across the network. Concentrations of Fe and Al were notable in that they were much higher along transect DG6 than anywhere else.

Table 1. Soil constituents by site.

Site	pH	OM%	Soluble Sulfur	P_ppm	Ca_ppm	Mg_ppm	K_ppm	Na_ppm	Fe_ppm	Al_ppm
DG1-1	6.80	0.205	6.5	8.5	88.0	29.0	8.5	19.5	28.5	21.0
DG1-2	6.00	0.265	5.5	6.0	73.5	23.0	8.0	12.0	17.5	18.0
DG1-3	5.30	0.325	6.0	5.0	73.5	22.0	5.5	10.5	14.0	17.5
DG1-4	4.95	0.355	6.0	4.0	66.5	17.5	5.0	10.5	12.5	18.5
DG1-5	5.65	0.28	5.5	4.0	65.0	19.0	5.0	11.5	13.5	18.5
DG1-6	6.25	0.245	41.0	8.5	128.0	97.0	28.5	462.0	31.0	39.0
DG1-7	5.20	0.14	6.0	7.0	69.5	18.0	16.5	13.0	15.0	26.0
DG3-1	6.05	0.22	6.5	6.0	81.0	26.5	7.0	18.0	14.0	26.0
DG3-2	6.00	0.22	6.0	4.5	80.5	24.5	5.5	12.5	10.5	21.0
DG3-3	4.55	0.905	10.5	10.5	160.5	55.5	14.0	18.0	29.5	53.0
DG3-4	5.05	0.2	6.0	5.0	71.5	19.5	9.0	15.0	18.0	24.0
DG3-5	4.70	0.27	6.0	5.0	66.0	18.0	7.5	11.0	20.0	19.5
DG3-6	4.75	0.26	7.0	6.0	80.0	21.5	7.0	13.5	23.0	22.5
DG3-7	4.65	0.36	6.5	8.0	89.5	21.5	7.5	10.5	28.0	32.0
DG3-8	5.20	0.215	6.5	6.5	71.5	19.5	6.0	11.5	24.0	35.0
DG4-1	5.90	0.305	7.0	11.0	94.0	30.0	8.0	16.0	10.5	17.5
DG4-2	5.15	0.295	7.5	8.0	175.0	23.0	7.5	11.0	13.5	50.5
DG5-1	5.80	0.165	6.0	5.5	85.0	25.5	6.5	10.5	10.5	17.5
DG5-2	4.65	1.12	11.5	12.5	104.0	37.0	23.0	17.5	30.0	39.0
DG5-3	4.90	0.64	7.5	11.5	98.5	27.5	9.5	10.5	44.5	54.5
DG6-1	5.40	0.285	12.5	33.0	104.0	21.0	13.5	14.5	65.0	292.5
DG6-2	5.25	0.355	9.0	22.0	82.5	27.0	10.5	14.5	52.5	155.5
DG6-3	4.75	0.395	12.0	23.0	84.0	29.0	11.0	12.0	78.5	265.5
DG7-1	6.65	0.175	6.5	6.0	87.5	36.0	13.0	25.0	23.0	40.0
DG7-2	5.70	0.255	6.5	9.0	83.0	29.0	23.0	15.5	20.0	38.5
DG7-3	5.60	0.255	7.0	8.0	105.0	29.5	11.5	15.0	22.0	47.5
DG9-1	5.15	0.37	8.0	7.0	87.5	33.5	12.0	20.5	10.5	17.0
DG9-2	5.70	0.235	6.5	5.5	95.0	32.5	9.0	17.0	12.5	20.5
DG9-3	5.00	0.245	6.5	8.5	85.5	24.5	7.0	16.0	17.0	28.5
DG9-4	6.00	0.395	7.0	6.5	120.0	52.0	17.0	17.0	16.0	28.0

A PCA of environmental variables (both measured and GIS-derived) is plotted in Figure 14. There is a considerable scatter of sites with no clear spatial groupings. The first axis, PCA1, accounted for 44.7% of the cumulative variance, mainly due to variables describing distance to the coast long NW and NE bearings. PCA2 accounted for an additional 17.4% of the variance (62.1% cumulative). Along this axis, straight distance to the ocean and salt deposition were the strongest spatial components.

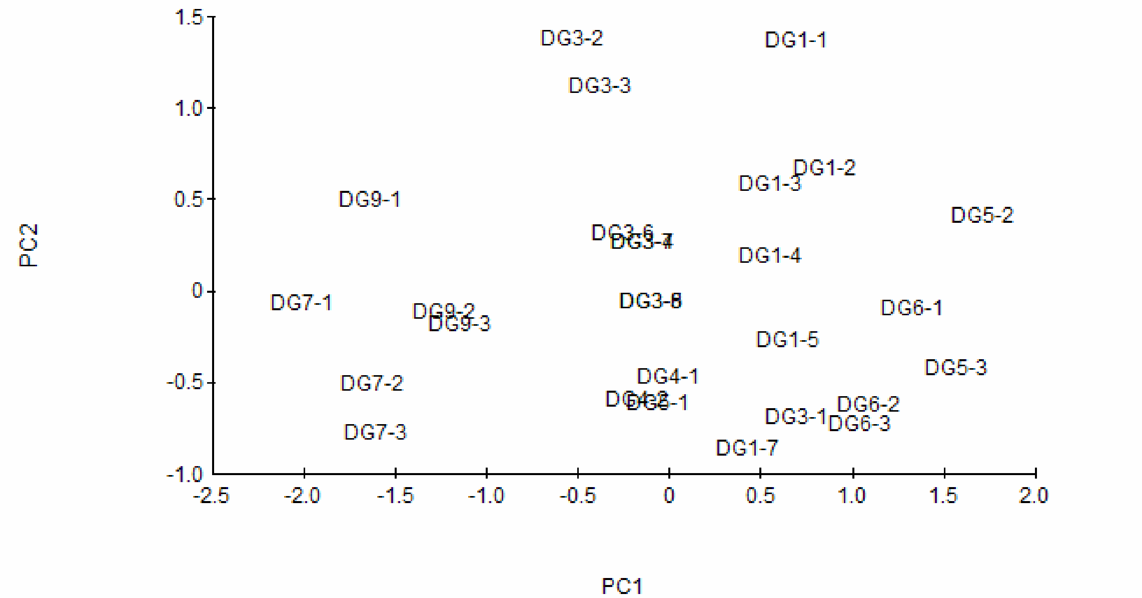

Figure 14. PCA of environmental variables.

When the GIS-derived variables (i.e., calculated not measured) are excluded from the dataset and PCA is run, the scatterplot looks quite similar and variance is explained largely by salt deposition along the first axis and concentrations of soil aluminum and sodium concentrations on the second axis.

<u>Vegetation</u>

A total of 44 vascular plant species and 1 non-vascular bryophyte occurring within the plots was recorded (Appendix II). The five most abundant species were *A. breviligulata*, *S. sempervirens*, *Deschampsia flexuosa*, *T. radicans*, and *M. pensylvanica.* Four salt marsh species, *Suaeda maritima*, *Distichlis spicata*, *Elymus virginicus*, and *Baccharis halimifolia* were found at two sites that encompassed a salt marsh – dune ecotone (DG1-6, DG9-4). Three freshwater wetland species, *Vaccinium macrocarpon*, *Juncus canadensis*, and *Juncus greenei*, were found at two sites where dune slack wetland – dune ecotones occurred (DG3-4, DG3-5). Seven of the 44 species are introduced, non-natives comprising 8.7% of the total cover (as calculated from summed cover class values). Only one state listed species, *Corema conradii* (Species of Special Concern) was found at a single site (DG6-3).

As mentioned previously, the two sites influenced by spring tides were excluded from the vegetation analyses. These sites are so strongly influenced by seawater, that they obscure the importance of other factors that contribute to variability among the rest of the sites, which are representative of true upland dunes. Also excluded were cover values for the 3 wetland species that occurred in two other plots. Thus, the dataset represented only upland dune communities. MDS showed a spatial separation of sites into two broad groups. One group (right cluster in Figure 15) includes species that are common to heathland landscapes, such as *Hudsonia tomentosa*, *Pityopsis falcata*, and *Lechea* *maritima*. The other group (left cluster in Figure 15) has communities more characteristic of early successional sand dune systems, with an abundance of *A. breviligulata*, *L. japonicus*, *S. sempervirons*, and *Toxicodendron radicans*. A separate PCA of species composition showed widely scattered sites with even less clustering (graph not shown). Species that accounted for the greatest proportions of this variability along the 1st axis included *A. breviligulata* and *Deschampsia flexuosa*, and *H. tomentosa* (beach heather). Along the 2nd axis, it was *T. radicans*, and *Prunus maritima* (beach plum).

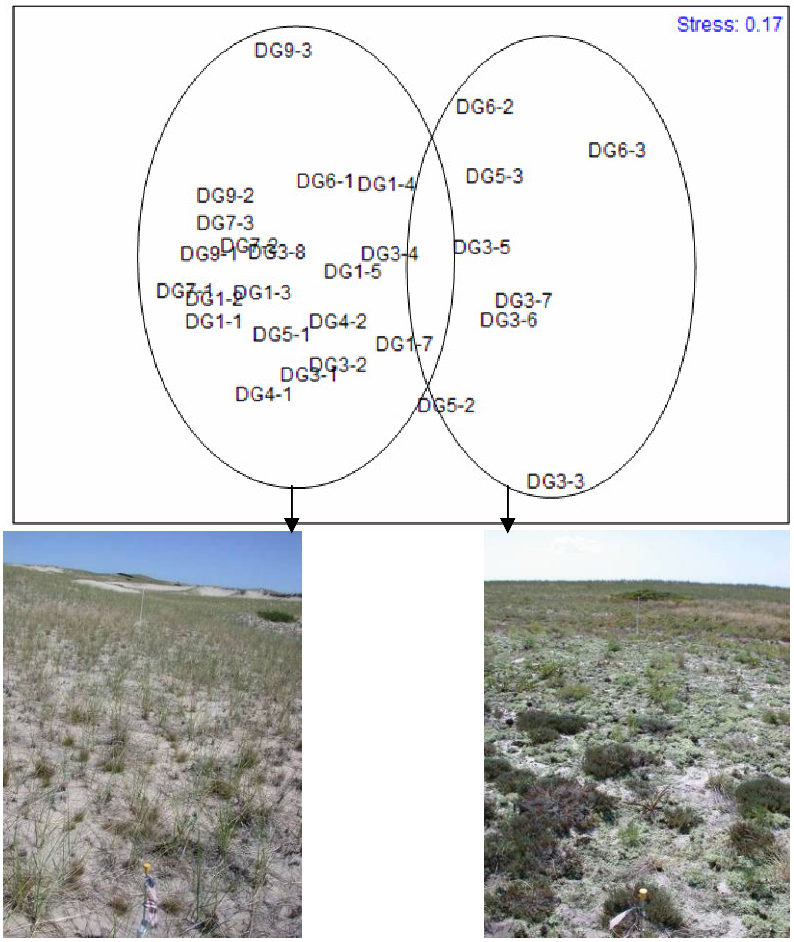

Figure 15. Multidimensional scaling of species composition (above) and images of sites representative of each group (below).

Results of the BIOENV analysis showed that species composition was best related to a grouping of environmental variables related to wind and salt influence - namely distance to the ocean along NE and NW bearings and concentration of Na, the most abundant cation in seawater (van der Valk 1974), in the soil ($R^2 = 0.92$).

A. breviligulata plants grew tallest at sites DG7-1, DG1-7, DG3-3, DG4-1, and DG9-1 (Figure 16). Of note is the fact that the tallest plants were mostly from bluff edge sites.

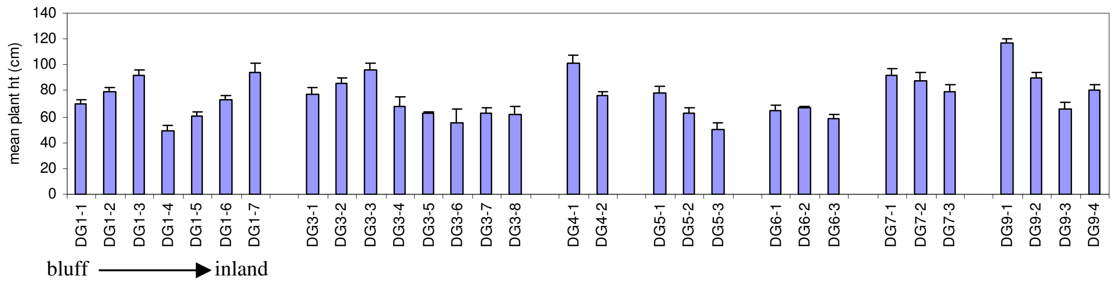

Figure 16. Mean plant height of *A. breviligulata* by site.

Multiple regression analysis suggested that mean aspect and NW wind exposure were the best combination of variables to explain *A. breviligulata* height. In the regression equation, heights were positively related to both variables, suggesting that sites facing N to NW, but with a high degree of protection from NW winds, have taller plants. By inference, this implies that shelter from northeast winds also is important. However, the relationship was very weak with a R^2 of 0.26 so little insight can be gained from this particular analysis. On a separate note, mean height was reasonably well correlated with litter coverage ($p \leq 0.001$), suggesting that sites with taller plants are more productive as well (Figure 17).

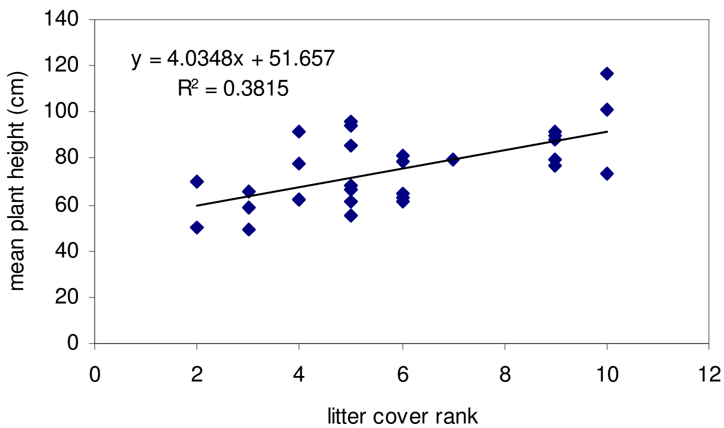

Figure 17. Linear regression of mean plant height of *A. breviligulata* vs. litter cover.

The number of species per site ranged between 2 and 17, with a mean value of 7 (Figure 18). The richest sites were DG6-2, DG 5-3, DG 3-5, DG 5-2, and DG 6-3, all of which are classified as old and largely protected from wind and salt spray. With respect to single environmental variables, species richness was best correlated with soil pH in a negative power relationship (Figure 19).

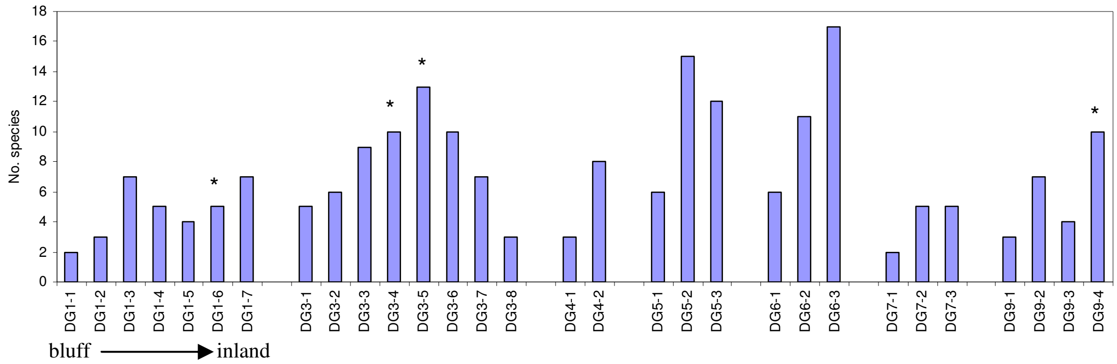

Figure 18. Number of species by site (asterisks indicate sites on salt marsh and freshwater wetland edges).

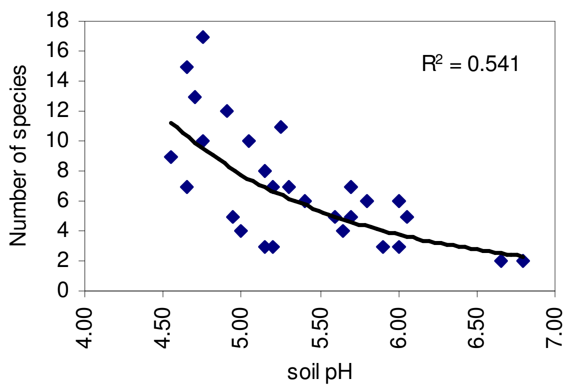

Figure 19. Species richness as a function of soil pH.

The equation of the multiple regression model, which included all GIS-derived parameters and all soil constituents, implies that richness was negatively related to both the mean slope and soil pH (R^2=0.63). In other words, the number of species is reduced in areas with steep slopes and high soil pH. This seems reasonable given that steep slopes are characteristic of active dune movement (particularly blowouts) and elevated pH is characteristic of sites close to the coast, since they are influenced by salt spray. Higher pH values are also associated with younger landscapes and vice versa (see Appendix III).

When sites were grouped into the young vs. old age categories, a significant difference in species richness is apparent with young sites being less rich than old ones (Figure 20). In addition, the cover of woody species was significantly higher at old vs. young sites. Differences in soil organic matter and pH were also evident and in agreement with what would be expected based on successional stage.

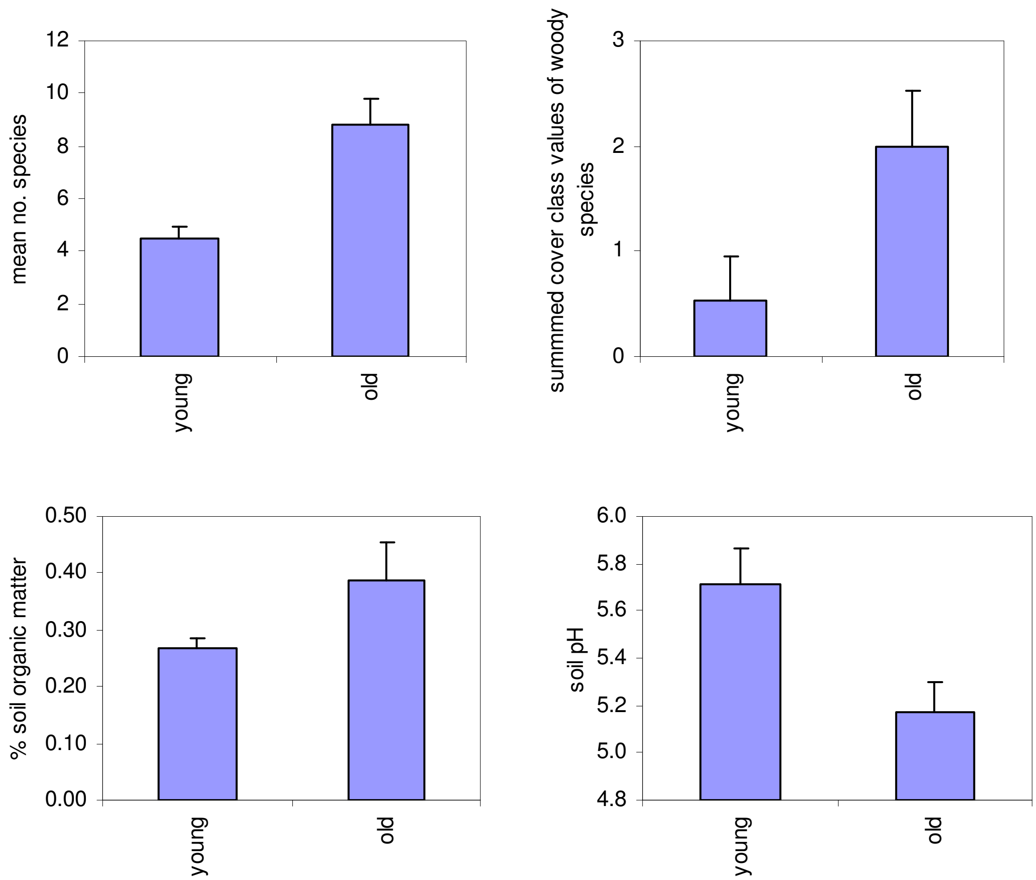

Figure 20. Mean number of species (top left), cover of woody species (top right), percent soil organic matter (bottom left) and soil pH (bottom right) in cores collected from young vs. old sites.

The presence of *Suaeda maritima* at DG1-6 and *Suaeda maritima*, *Distichlis spicata*, *Elymus virgincus*, and *Baccharis hamilifolia* at DG9-4 reflects salt water intrusion during spring tides. The abundance of this or any other salt marsh species at these sites will serve as a good indicator of sea level rise. Similarly the presence of freshwater species such *Juncus* spp. and *Vaccinium macrocarpon* at the edges of certain sites along transect DG3 will serve as an indication if changes in the groundwater table – due to sea level rise, groundwater withdrawal, or other factors.

Discussion

The 2005 monitoring effort described in this report has generated a useful baseline dataset with which to characterize biotic and abiotic conditions of dune grassland habitat. From this information, and supporting data from the existing literature, a general conceptual of plant community structure and function can be developed. There are, however, some complexities in interpreting the data that should be kept in mind. For example, with respect to salt spray, the largest doses of salt came from storms (i.e., Nor'easters in May). During these kinds of events, salt may have little adverse effect if there is heavy rainfall during that time. Salts would be washed off any aboveground plant surfaces and percolate down through the root zone. Because soil organic matter content is very low, only a small proportion of positively charged ions (Na, Mg, K) would become adsorbed within the root zone and virtually all chloride would pass right through to the groundwater table.

Another factor is the timing of storm events. The strongest storms frequently occur during times of the year (October through May) when plants are either entering into, in, or just emerging from dormancy – a period when adverse conditions would have little effect on plant physiology. In addition, the tolerance of leaves to the direct effect of salt spray does not necessarily indicate tolerance to elevated root zone salinities and vice versa (Sykes and Wilson 1988).

The analysis also suffers from poor data on site history - in particular, age (successional stage) and disturbance. Geological dating has helped to elucidate rates of succession for the Indiana dunes along Lake Michigan (Olson 1958) and a new technique called optically stimulated luminescence (OSL) dating may be useful to obtain better resolution of landscape age at some point in the future for CACO. To complicate matters, the vegetation landscapes have been, to some degree, shaped by one or many past disturbances (e.g., hurricanes), which could not be quantified. Such events can be extremely important in determining the trajectory of succession since vegetation zonation patterns are disrupted and replaced by a mosaic of disturbance patches that differ in recovery times and, therefore, species composition (Turner et al. 1998, Stallins and Parker 2003).

Although soil moisture undoubtedly plays a role in plant establishment, growth and survival, it was not measured in this study for a number of reasons. From a plant perspective, soil moisture is quite difficult to characterize since different species have different rooting depths. Thus, two plants growing side by side may experience very different moisture regimes. The same problem is encountered for different aged plants of the same species, not to mention that drought tolerance within a species can change with ontogeny, irrespective of rooting depth. Furthermore, many hundreds of instantaneous measurements in time, space and depth would be necessary to adequately characterize soil moisture conditions over the course of a growing season. Within a relatively uniform substrate type, however, soil moisture is highly correlated with % organic matter, which was quantified in this study. In fact soil organic matter may be a more integrative indicator of soil moisture regime over long time scales.

Despite these limitations, the data do provide a basic picture of the physical and biological environment and how they are related to succession (Figure 21). Important factors appear to be proximity to the coast and as strong winds from the NE deposit both salt spray and sand near the bluff edge, particularly along the ENE to NNE part of the coastline. Geophysical processes are also important in that sites will become more distant from these influences where coastal accretion is occurring. The decreased influence of physical factors will allow succession to proceed at a faster rate. As coastal erosion takes place, the opposite will occur. Sites getting closer and closer to the eroding bluff will increasingly be affected by salt spray, wind, and sand deposition – conditions which suppress or reverse succession and reduce species richness. Along these lines, Roman and Nordstrom (1988) reported that erosion rates of 4-5 m per year can result in the persistence of an overwash-type (i.e., early pioneer) community. Some species, such as beechgrass, may actually benefit from enrichments of various cation nutrients (e.g., Ca, K) contained in salt spray (van der Valk 1974, 1977). This, along with a moderate accretion of sand, which is known to stimulate growth in *Ammophila breviligulata* (Maun and Lapierre 1984), may be why these plants tend to be taller at bluff-edge sites.

More general climatic factors such as precipitation and temperature will also influence dune communities. Prolonged drought should create or maintain early successional communities while periods of high precipitation will promote the development of later stages. A cooler climate enhances organic matter accumulation due to reduced microbial degradation and vice versa (Sevnik 1991). During the process of dune migration, communities may be buried and eventually uncovered as dunes pass over them. This can be tracked through regular acquisition and analysis of aerial photography.

Finally, local factors may also influence communities on a micro-scale. It is well-documented that disturbance by humans in the form of foot or vehicle traffic re-sets the successional sequence. In terms of natural processes, animals such as rabbits and deer play a role in the dispersal of seeds through the system. The presence of *Morella pensylvanica* (northern bayberry) can facilitate the establishment and growth of other plants through its ability to fix atmospheric N, which is eventually incorporated into the soil through litterfall and decomposition (Morris et al. 1974, Shumway 2000). Furthermore, sites in elevation depressions can accumulate wind-blown detritus and seeds (Baptista and Shumway 1998). This would have the effect of concentrating organic matter, which, in turn, would support the growth of secondary species including woody shrubs and trees. Previous observations on the relationship between soil organic matter and vegetation associations in the Province Lands support this model (Koske and Gemma 1992). In later successional stages, various mixtures of pitch pine (*Pinus rigida*), oak (*Quercus velutina*, *Quercus alba*), and beech (*Fagus grandifolia*) may develop. While these mixed forest types currently exist in certain areas of the Province Lands, outcroppings of remnant soil horizons observed on dune faces are indicative of their broad expanse in the past.

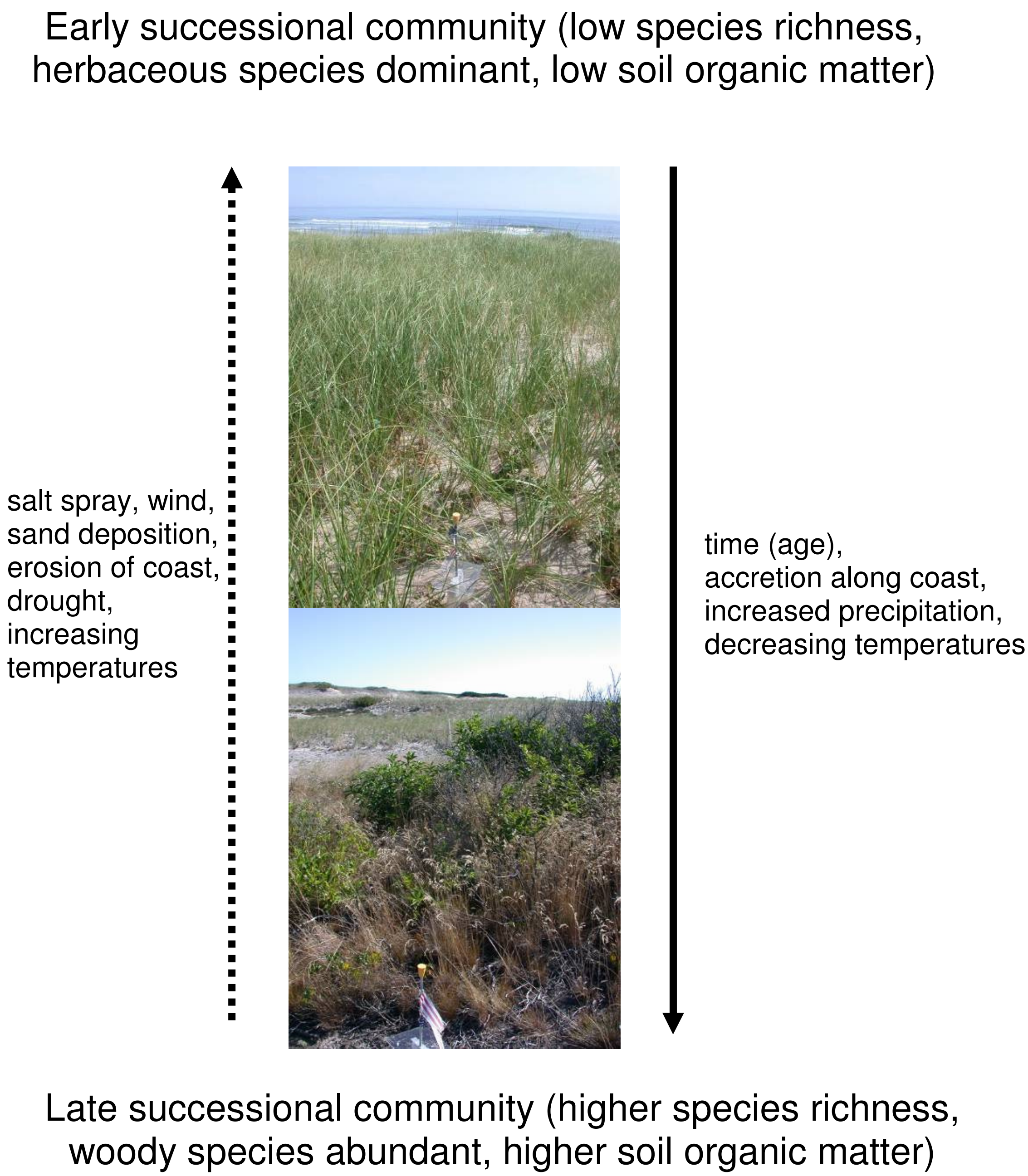

Figure 21. Basic conceptual model for plant communities of the dunes.

Future monitoring

All sites should be surveyed again no later than 2015 (10 years) to assess temporal variability in vegetation. Given the slow rate of change in these communities, 10 years is probably a sufficient frequency for this system. However, data can always be collected opportunistically – particularly if there is a major disturbance event (such as a hurricane) within the time period between surveys. Environmental variables should also be assessed in the same manner as described in this study so that some estimate of year to year variability can be made. New GIS products, such as an updated DEM and aerial photography, can be utilized as they become available to evaluate gross changes in the physical landscape. For example, periods of dune movement and stabilization across the Province Lands from 1938 - 2003 are currently being analyzed by Dr. Steve Forman (University of Illinois, Chicago). This information will provide valuable information on vegetation development over a 60 year period.

Some of the bluff-edge sites will eventually be lost through erosion while new dune areas will be created through accretion. Therefore, it will be necessary at some point in the future to establish more sites to compensate for losses and to accommodate any significant expansion in dune habitat. In reality, many more vegetation plots could be established and surveyed if there is no corresponding salt spray and wind monitoring to be conducted, which requires that data be collected from all sites in a single day. In contrast, vegetation communities can be assessed over a period of 1-2 weeks or more without having to be concerned about temporal variability during that period. Quantifying salt spray and wind across a larger spatial boundary would be informative but is probably unnecessary. This study has provided information about how ground wind, sand transport, and salt spray conditions at CACO are linked to position along the coastline and distance away from the bluff edge, a relationship that is not only intuitive but has been shown in other studies in New England (Griffiths and Orians, 2003a,b, 2004). Accordingly, GIS-derived proxy variables could be used in analyses of vegetation data from new sites. Increasing the sample size of the monitoring program would effectively provide a more expansive picture of dune habitat while increasing the power to detect changes through time.

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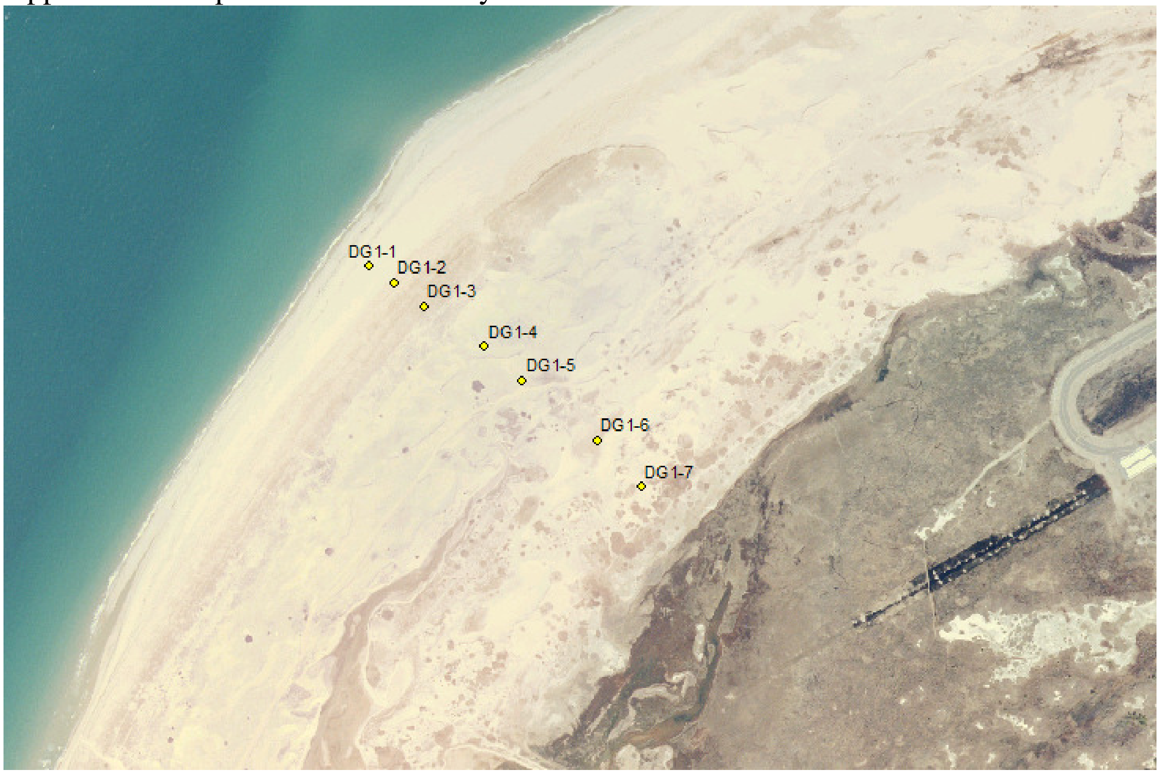
Appendix I. Maps of site locations by transect.



Site locations along DG1.

Site locations along DG3.

Site locations along DG4.

Site locations along DG5.

Site locations along DG6.

Site locations along DG7.

Site locations along DG9

Appendix II. List of vascular plant species recorded in plots (2005).

Species	Status	Sum CC	Frequency
Ammophila breviligulata	native	228	29
Solidago sempervirens	native	63	25
Deschampsia flexuosa	native	55	13
Toxicodendron radicans	native	52	13
Morella pensylvanica	native	38	10
Prunus maritima	native	33	9
Artemisia campestris ssp. caudata	native	32	7
Lathyrus japonicus	exotic	29	8
Hudonsia tomentosa	native	27	7
Pityopsis falcata	native	21	7
Lechea maritima	native	17	7
Rumex acetosella	exotic	9	2
Distichlis spicata	native	8	1
Pinus rigida	native	8	3
Arctastaphyllos uva-ursi	native	6	1
Artemisia stellariana	exotic	6	4
Dichanthelium depauperatum	native	6	2
Bromus tectorum	exotic	5	2
Cyperus grayi	native	5	3
Dichanthelium acuminatus	native	5	2
Rosa virginica	native	5	3
Juncus greenei	native	4	2
Panicum lanuginosum	native	4	2
Rosa rugosa	exotic	4	2
Pseudognaphalium obtusifolium	native	3	2
Achille millifolium	exotic	2	1
Andropogon virginicus	native	2	1
Chamaesyce polygonifolia	native	2	2
Corema conradii	native	2	1
Elymus virginicus	native	2	1
Lactuca canadensis	native	2	1
Onothera biennis	native	2	1
Parthenocissus cinquefolia	native	2	2
Polygonella articulata	native	2	2
Prunus serotina	native	2	1
Suaeada maritima	native	2	2
Baccharis halimifolia	native	1	1
Cakile edentula	native	1	1
Hieracium sp.	unknown	1	1
Hudsonia ericoides	native	1	1
Juncus canadensis	native	1	1
Linaria vulgaris	exotic	1	1
Schizachyrium scoparium	native	1	1
Vaccinium macrocarpon	native	1	1